J Neurosurg 121:1297–1313, 2014

Expanding neurosurgery

The 2014 AANS Presidential Address

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The history of medicine is replete with innovations in neurosurgery that have spurred further developments across the medical spectrum. Surgeons treating pathologies in the head and spine have broken ground with new approaches, techniques, and technologies since ancient times. Neurosurgeons occupy a vital nexus in patient care, interfacing with the clinical symptoms and signs afflicting patients, the pathology at surgery, and imaging studies. No other physicians occupy this role within the nervous system. This power of observation and the ability to intercede place neurosurgeons in a unique position for impacting disease. Yet despite these pioneering achievements, more recently, forces in the workplace may be challenging neurosurgery's opportunities to contribute to the future growth of the neurosciences and medicine. The authors posit that, in the current health care climate, revenue generation by neurosurgical clinical activity is valued by the system more than neurosurgical research and academic output. Without providing the talented stream of new neurosurgeons with the opportunities and, in fact, the directive to achieve beyond simple financial success, the specialty is missing the opportunity to optimize its progress. The authors contend that the key to remaining relevant with the incorporation of new technologies to the treatment of neurosurgical patients will be to be flexible, open-minded, and nimble with the adaptation of new procedures by training and encouraging neurosurgical residents to pursue new or neglected areas of the specialty. Only by doing so can neurosurgery continue to expand.
(http://thejns.org/doi/abs/10.3171/2014.8.JNS141791)

Key Words • **AANS 2014 presidential address** • **history of medicine** • **expanding neurosurgery** • **surgical innovation**

The Big Bang theory is the prevailing cosmological model for the early development of the universe. Let me use this metaphor for the expansion of our specialty over the millennia, but most significantly over the past century. Neurosurgeons, since ancient times, have been great innovators. As neurosurgeons, our impact on medicine in general surpasses our absolute numbers; however, I am concerned that the forces conspiring in our workplace may be challenging our opportunities to contribute to the future growth of the neurosciences and medicine.

Neurosurgery in the Ancient World

The earliest evidence for neurosurgery is the widespread discoveries of human skulls showing cranial trepanation from archaeological sites in the Americas, Oceania, Africa, and Europe. The oldest trepanations were found in North Africa and may date to about 10,000 BC.[21] As far as we know, trepanation was first practiced in Europe during Neolithic times.[49] The oldest specimens in the New World are more recent examples dating to 400 BC from Peru, where the Inca were still practicing trepanation when the Spanish arrived in 1532.[58]

The motivation for trepanation is not clear, but several theories have been proposed. So many skulls in their tombs have been trepanned that it seems probable that the operation had some ritual significance.[32] Hippocrates, on the other hand, describes the use of trepanation to treat certain types of head wounds.[50] In support of the head trauma–related indication, it has been noted that in trepanned skulls in ancient Peru, there is a predilection for damage of the left side of the skull, consistent with blows from right-handed assailants (Fig. 1).[54] Information from more recent East African practitioners indicates the motive of the Kisii people is relief of headache.[42]

Skulls from archaeological sites showing postoperative healing suggest an impressive rate of success. This observation indicates that care was taken to avoid laceration of the meninges, a measure which would lessen the risk of blood loss and infection. What is truly amazing is that some skulls show multiple healed trepanned openings. One extreme example is a skull from Cusco, Peru, which has 7 trepanned openings, all of which show healing (Fig. 2).[3]

At the same time that trepanning was occurring throughout the world, ancient Egyptians were pioneering

This article contains some figures that are displayed in color online but in black-and-white in the print edition.

Fig. 1. Photograph of a skull from Peru showing evidence of trepanation, with damage on the left side of the skull, consistent with blows from right-handed assailants. (Reproduced with permission from Antonio de la Cova, Ph.D.)

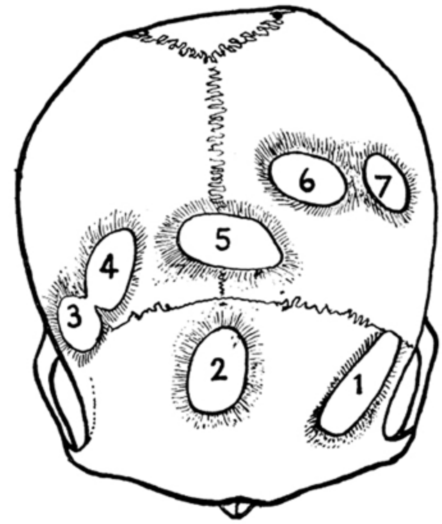


Fig. 2. Illustration of skull from Peru showing location of 7 trepanned openings. (Reproduced with permission from Notable examples of early trephining, Brothwell DR: in Oakley KP, Brooke WMA, Akester AR, et al [eds]: **Contributions on Trepanning or Trephination in Ancient and Modern Times.** Copyright © 1959, London: Royal Anthropological Institute of Great Britain and Ireland.)

other neurosurgical techniques. Egyptian skulls from the 12th and 18th dynasties (2000–1300 BC) demonstrate an evolution in skull base surgical techniques with the excerebration procedures used during the process of mummification.[48,53] The approach adjacent to the occipital condyle was devised by Egyptian embalmers to remove the cranial contents. Being wary of any damage to the deceased body, ancient Egyptians later performed postmortem transnasal surgery for removal of cranial contents without altering the skull or face. Initially, the skull defect was made in the ethmoid region, but later a transsphenoidal route was chosen.[19,25,31,43] The removal of the cranial contents is remarkable, given the lack of imaging or light source (Fig. 3).[31] The Egyptians believed that the heart was the most important organ, while the brain was unnecessary for life. Such little importance was given to the brain that, while other organs were desiccated in salt and returned to the body cavity, the brain was discarded and the cranial cavity was filled with molten resin.

The Crucible Period

Postmortem understanding of the brain and spinal cord continued to grow through the ancient and medieval periods, with the contributions of such luminary anatomists as Galen, Avicenna, Vesalius, and Willis, but the modern history of neurosurgery really developed in the late 19th century when surgeons began to specialize. With a determination to become a surgeon who operated upon the nervous system, William Macewen used Ferrier's data regarding the motor cortex to diagnose and operate on a young boy with jacksonian seizures following trauma.[41] Thus, the crucible years began, and the stage was set for the emergence of Harvey Cushing in the field.

The Cushing Era

Continuing in the traditions of earlier physicians, surgeons in the new field of neurosurgery continued to make tremendous contributions to medicine in general (Fig. 4). Cushing was clearly the first ground-breaking neurosurgeon whose impact was felt across medicine (Fig. 4A). While Cushing's accomplishments with cranial neurosurgery are well recorded, such as the reduction in mortality of cranial surgery from more than 70% to less than 10%, his other contributions during this period may be less appreciated.

Cushing's first introduction to anesthesia occurred at Harvard while he was a third-year medical student, when he was asked to etherize a patient with a strangulated hernia. Although the patient vomited, aspirated, and died during the lecture, the surgery was completed to demonstrate the surgical technique. In his diary, Cushing wrote of the experience, "I slunk out of the hospital, walked the streets of north Boston the rest of the afternoon, and in the evening went to the surgeon's house to ask if there was any possible way I could atone for the calamity to the man's family before I left the Medical School and went into some other business. To my perfect amazement I was told it was nothing at all, that I had nothing to do with the man's death, … that I had better forget about it and go on with Medical School. I went on to Medical School but I have never forgotten about it."[2] After this introduction, Cushing then wagered with his friend, Ernest Codman, as to who could learn to provide the best anesthesia. In an effort to improve their skills, Cushing created the "ether chart," the first documentation of vital signs such as breathing, pulse rate, and temperature during an operation.[2]

Somewhat later in his career, Cushing introduced new modalities to intraoperative monitoring. Among them were the measurement of blood pressure and precordial auscultation. In his paper, "Some Principles of Cerebral

Surgery," published in JAMA in 1909,[8] Cushing dedicates a paragraph to the importance of continuous blood pressure monitoring. He knew that chloroform decreased, but ether increased blood pressure, and he preferred using ether for his cases to avoid the risk of hypoperfusion. Even as late as 1930, other surgeons did not appreciate the benefits of continuous blood pressure monitoring during surgery. Cushing had visited Scipione Riva-Rocci in Pavia, Italy, in 1901, and when he returned to Baltimore he introduced the Riva-Rocci sphygmomanometer for continuous blood pressure monitoring.[8] He also introduced the notion of continuous precordial auscultation for the anesthetized patient.[30] This was achieved by using the transmitter of a phonendoscope over the chest and connected by a long tube to the anesthetist's ear.

Understanding that all of these functions would interfere with surgical focus, Cushing asked Samuel Griffith Davis to become his first "neuroanesthetist," and this was the birth of neuroanesthesia.

Neurosurgery and the Birth of Neuroradiology

Cushing was also involved in the birth of neuroradiology, as he personally made the first x-rays used to treat a patient with a neurological disability. Within 6 weeks of Roentgen's report of the new "X-rays" in December 1895, Cushing, a house pupil at Massachusetts General Hospital, wrote to his mother: "Professor Roentgen may have discovered something with his cathode rays that may revolutionize medical diagnosis."[23] Not even 1 year later, after Cushing had moved to Johns Hopkins, a patient presented with Brown-Sequard syndrome from a bullet wound to the neck, and Cushing used the new tube to obtain the x-ray images shown in Fig. 5.[6] Some 29 years later, Cushing presented to the American Roentgen Society: "It was the fall of 1896 that I went to Johns Hopkins and made the first roentgenograms taken there, with the aid of a decrepit and perverse static machine as big as a hurdy-gurdy and operated in the same way, by turning the crank. … I shall now confide in you, that the plates were the result of exposures averaging 35 minutes."[23]

Besides Cushing, other neurosurgeons are recognized as innovative contributors to the development of radiology as a specialty, and the contributions of Walter Dandy are important in the development of neuroradiology.

Walter Dandy

At the age of 32, while still a resident, Dandy (Fig. 4B) introduced air ventriculography.[12] The techniques of ventriculography and pneumoencephalography were first published in 1918. Heuer and Dandy reported a series of patients in whom brain tumors were diagnosed from x-ray studies. Dandy then surmised that about half of tumors not seen on plain x-ray could be localized if the ventricles were filled with air. Dandy had developed the idea for air contrast after seeing pneumoperitoneum when "the X-ray of the abdomen revealed separation of the liver from the diaphragm by a collection of gas."[11] Heuer and Dandy also described diagnosing the first calcified intracranial aneurysm by x-ray (Fig. 6).[27]

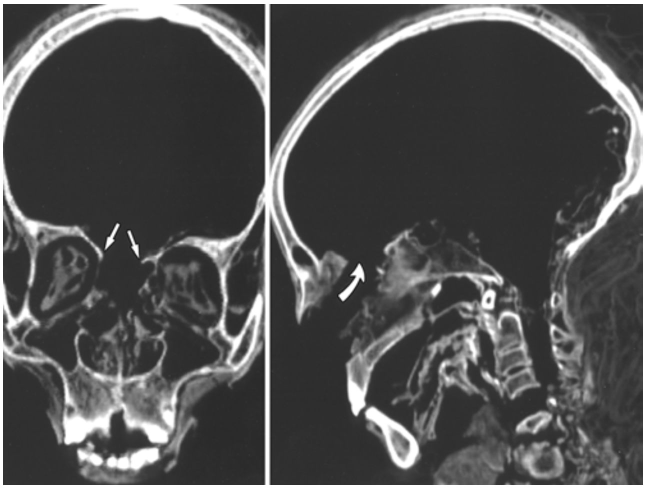


Fig. 3. Imaging showing ancient Egyptian skull with cranial contents removed; *arrows* denote the routes used. (Reproduced with permission from Hoffman H and Hudgins PA: Head and skull base features of nine Egyptian mummies: evaluation with high-resolution CT and reformation techniques. **Am J Roentgenol 178:**1367–1376, 2002. [Reprinted with permission from the *American Journal of Roentgenology*.])

Cushing and Dandy were not the only neurosurgeons to make a significant impact in imaging of the nervous system. Merrill Sosman, recognized as the first neuroradiologist in the US (Fig. 4C), teamed up with Cushing at the Brigham and with other neurosurgeons such as Bailey, Cairns, Horrax, Martin, Mackenzie, Putnam, and Van Wagenen. In New York, the team of neurosurgeon Davidoff and radiologist Dyke published the classic *The Normal Encephalogram*. This close relationship between neurosurgeons and neuroradiologists was as natural back then as it remains today. When the American Association of Neurological Surgeons (AANS) was organized in 1931 as the Harvey Cushing Society, 4 radiologists were among the 36 names considered for membership, and 2 of the charter members (Chamberlain and Sosman) were radiologists.

Breaking Ground in Other Fields

These are but a few of the early anecdotes of the pioneers of our specialty who have had a tremendous impact in medicine in a broader context. Subsequently, neurosurgeons have continued through our short history to have impact beyond the confines of our specialty. I provide but a few more examples for you to consider:

Cushing himself is considered the father of pituitary endocrinology, following the publication of his book *The Pituitary Body and its Disorders* in 1912.[7] This fascinating text described the symptoms and signs of many patients with functional and nonfunctional pituitary tumors. It was the seminal publication on pituitary endocrinology and tumors.

Alfred Adson was a talented peripheral nerve surgeon who made other early contributions not widely recognized (Fig. 4D). Adson pioneered treatment of such varied diseases as intramedullary spinal cord tumors, thoracic outlet syndrome, glossopharyngeal neuralgia, essential hy-

Fig. 4. Photographs of Drs. Harvey Cushing **(A)** (photograph by Doris Ullman); Walter Dandy **(B)** (Courtesy of the AANS Archives); Merrill Sosman **(C)** (Reproduced with permission from **Harvard University Gazette**, in which obituary first appeared in January 1960, pages 75–76 [photograph also reproduced in Dealy JB Jr: **J Neurosurg 17:**555–557, 1960[14]]); Alfred Adson **(D)** (Courtesy of the Society of Neurological Surgeons); William Bovie **(E)** (Courtesy of the Albion College Archives and Special Collections); Irving Cooper **(F)** (Courtesy of John Hogle, photographer); Gerard Guiot **(G)** (Reproduced from Pituitary, vol 11, 2008, pp 337–345, The evolution of extracranial approaches to the pituitary and anterior skull base, Grosvenor AE, Laws ER [Fig. 9 right]. With kind permission from Springer Science and Business Media); and Gazi Yaşargil **(H)** (Reproduced with permission from Tew JM Jr.: M. Gazi Yaşargil: Neurosurgery's man of the century. **Neurosurgery 45(5):**1010–1014, 1999).[55]

perhidrosis, Raynaud's disease, and idiopathic dilation of the colon via sympathetic ganglionectomy. He was also the first to describe facial nerve preservation in parotid tumor surgery.[1] Cushing described operating on brachial plexus tumors, performing nerve decompressions, suture repair for neuromas-in-continuity, and facial reanimation, and was the first to attempt spinal accessory–facial nerve coaptation in 1903.

Dandy also performed cranial nerve surgery, such as vestibular nerve section for Meniere's disease and trigeminal nerve decompression for neuralgia. He was also interested in spasmodic torticollis and described a method for denervation.[10] Dandy was convinced that the only good functional result after nerve injury came from direct nerve repair, but many patients came to him months or years after injury. This illustration shows a girl who presented 15 months after injury (Fig. 7); Dandy excised the neuromas and shortened the humerus to enable reanastomosis of the nerves. Ten years later, the patient regained some wrist extension.[9]

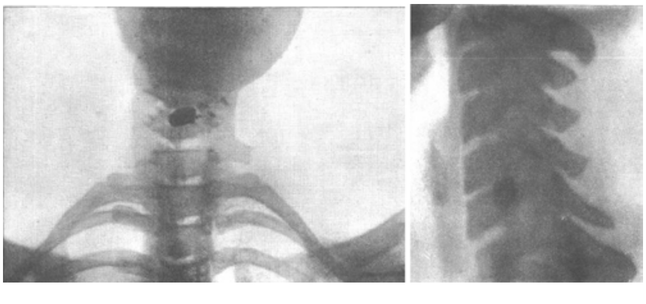


Fig. 5. Radiographic images obtained by Cushing with the new x-ray imager. (Reproduced from Cushing H: Haematomyelia from gunshot wounds of the spine. A report of two cases, with recovery following symptoms of hemilesion of the cord. **Am J Med Sci 115:**654–683, 1898.)

Cushing and Bovie

Battling blood loss offered a special challenge to neurosurgeons, particularly before the introduction of electrocautery.[59] Cushing's crucial collaboration with William Bovie (Fig. 4E), in which they parlayed Bovie's novel electrosurgical apparatus, conquered this major obstacle. As he had done at other times in his life, Cushing recognized a potential new technology that impacted all of surgery. The nature of their collaboration—two experts in their respective fields who were passionate about their work, working side by side in the operating room—resulted in progress that surpassed all predecessors in the field.

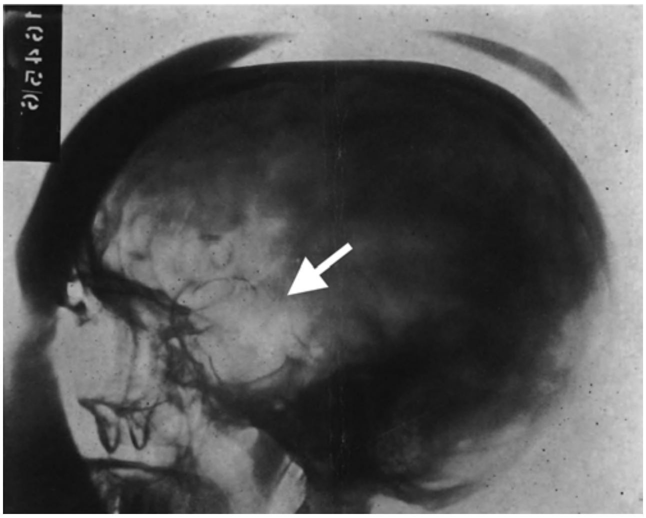


Fig. 6. Radiograph obtained by Heuer and Dandy showing calcified intracranial aneurysm (*arrow* added). (Reproduced from Heuer GJ, Dandy WE: A report of seventy cases of brain tumor. **Bull Johns Hopkins Hosp 27:**224–237, 1916.)

Irving Cooper

Irving Cooper, the flamboyant and brilliant functional surgeon, was the father of cryosurgery (Fig. 4F). During his career, he devised many techniques for lesioning targets in the thalamus and basal ganglia, including intentional ligation of the anterior choroidal artery and the use of agents such as alcohol to produce chemotoxic lesions.[13] He later developed the use of liquid nitrogen to induce cryothermic damage.[5] In 1962, Cooper, with help from an engineer and a cryobiologist, designed the first cryosurgical probe for use in the human brain. He advanced his techniques for movement disorder surgery for essential tremor using liquid nitrogen to produce the definitive thalamic lesion (see videos in Hornyak et al.[33]). A reversible test lesion was made by cooling the probe to 10°C. If tremor and rigidity were abolished without side effects, a permanent lesion was created by incrementally cooling the probe tip with liquid nitrogen. Although controversial, this work led to an explosion of interest in liquid nitrogen and its acceptance as a standard treatment in many specialties.

Gerard Guiot

Another leader during this period was Gerard Guiot in France (Fig. 4G). Beyond his pivotal role in advancing transsphenoidal surgery and his contributions to stereotactic neurosurgery, his other contributions to the advancement of surgery have not been well recognized. Guiot was a pioneer in intracranial and skull base endoscopy, performing the first endoscopic approach to a pituitary tumor in 1962.[39] Guiot was equally interested in maxillofacial surgery. Plastic surgery blossomed as a separate specialty during World War I, but it was not until the early 1960s, when plastic surgeon Paul Tessier introduced his neurosurgeon colleague to the new "craniomaxillofacial team," that neurosurgeons became involved in these procedures.

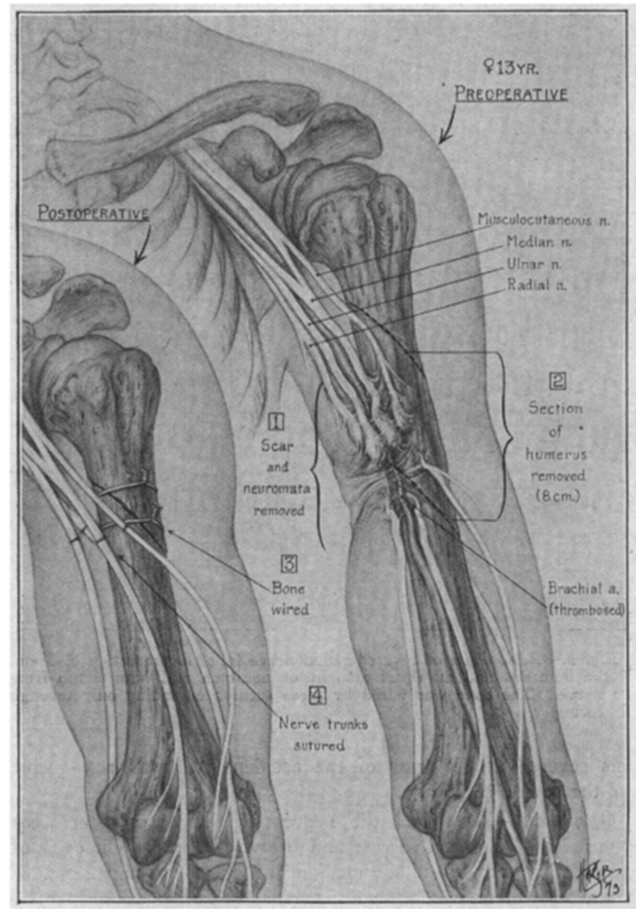


Fig. 7. Illustration showing functional nerve injury in a 13-year-old girl in whom Dandy excised the neuromata, shortened the humerus, and reanastomosed the nerves. (Reproduced with permission from Dandy WE: A method of restoring nerves requiring resection. **JAMA 122:**35–36, 1943. Copyright © [1943] American Medical Association. All rights reserved.)

That same year, as they planned a very complicated operation for hypertelorism in a patient with Crouzon's syndrome, it was clear that a transcranial approach would be necessary to expose the orbits and the ethmoid region to completely reconstruct the face. While Tessier went on to be recognized as the father of modern craniofacial surgery, this would not have been possible without Guiot's input.

Gazi Yaşargil

At the advent of the 1960s, Gazi Yaşargil ushered in a new era of microsurgery as applied to vascular and tumor pathologies (Fig. 4H). Yaşargil, with Peardon Donaghy in Vermont, had performed the first preclinical studies on animals to demonstrate the feasibility of bypass procedures using microsurgical techniques.[18] While he became a celebrated surgeon and a pioneer in microsurgery, he was continuing to hone his knowledge of cerebral angiography, and together with neurosurgeons Krayenbuhl and Huber, wrote a definitive text on the subject in the early 1980s.[34]

Such pioneering examples can still be found in neurosurgery today, with present-day neurosurgeons having far-reaching influences. For example, Garnette Sutherland in Canada has pioneered the use of a remote robot to perform in the operating room (http://www.youtube.com/watch?v=k5nWDPq3lAg), and also directly within an MRI magnet bore.

The feature common to all of these contributions by these luminary individuals is the impact that they have had in fields beyond neurosurgery. We need to remind our young trainees that as neurosurgeons we occupy a vital nexus in patient care, as we interface with the clinical symptoms and signs afflicting our patients, the pathology at surgery, and imaging studies. No other physicians occupy this role within the nervous system. This power of observation and the ability to intercede place us in a unique position for impacting disease.

Innovation and Time Effort

Several lessons can be learned from our review of global achievements in technological innovation. I would like to review some very interesting observations of the technological developments of the past one and a half centuries. Notable economists Alexander Field in California and Brent Goldfarb and David Kirsch in Maryland have made some fascinating observations. If one looks over the past 150 years, the most productive decade from a technological standpoint is the decade of the Great Depression.[22] While economic productivity was obviously disastrous during the Depression, the period between 1929 and 1941 was not disastrous from the standpoint of long-term growth. In fact, the opposite was true.

The Depression years experienced exceptionally high multifactor productivity growth rates, partly as a result of serendipity, and in part for reasons that are very relevant to our own specialty.[22] For example, within the railroad industry, the downturn fostered a search for innovations that enabled firms to get more out of what they had. The 1930s were characterized by progressive programs in a large number of industries, including chemicals, long-distance communication, electrical machinery, structural engineering, and aviation. Field observed that "Many of these sectors relied upon and benefited from scientific advances in a way that 19th century industry leaders did not. Economic progress was also fostered by a system of privately funded R&D labs that reached maturity and operated during the 1930s relatively undistorted by the previous and subsequent demands of the military."[22]

In addition, the high unemployment rates and time availability of savvy innovators provided an excellent opportunity for cultural innovation not seen in the surrounding decades, which yielded such notable achievements as short wave and FM radio, sulfa drugs, synthetic rubber, radar, color photography, the helicopter, commercial television, nylon, and the jet engine (Goldfarb B, Kirsch DA, presented at the Annual Meeting of the Social Science-History Association, 2010; http://smith.vpmdev.com/files/Documents/Centers/CFP/WhenAreThereNotBubbles.pdf).

Furthermore, Field noted, "The Hoover Dam, the George Washington Bridge, the Golden Gate and Oakland Bay Bridges, the Lincoln Tunnel, and the Pennsylvania Turnpike, Merritt Parkway, and Pasadena Freeway are notable achievements in civil engineering that occurred in the period from 1929 to 1941."[22]

Labor productivity grew during the Depression in the absence of new capital expenditures. Government and university researchers helped design principles for surface transport and residential planning for the ensuing automobile age. Field remarked "exhibits highlighting these achievements, in particular the General Motors exhibit and 'Democracity,' were the standout attractions at the 1939–1940 New York World's Fair." and concludes that "the years 1929 to 1941 were the most technologically progressive of any period in U.S. economic history."[22] One can assume that this is because of a demand for innovation and the availability of talented individuals to focus their efforts on this need. So why is this observation relevant for neurosurgery?

Neurosurgical Economic Productivity

All practicing neurosurgeons are familiar with the quality of resident applicants we attract to neurosurgery. Our training programs are particularly competitive, in that we have several hundred applicants who apply for the roughly 200 training spots in the United States. This is evident from the recent match data from the National Resident Matching Program (NRMP).[47] In fact, we are among the most competitive of all specialties, when we consider the percentage of U.S. medical students who match in our programs. This is also evident from the Board scores of the entering class and the research experience and publication records of our applicants.[47]

Furthermore, if one reviews the labor productivity of neurosurgeons compared with other specialties, we represent a hard-working group. The average neurosurgeon is producing approximately 12,000 relative value units (RVUs) per year, which is up to three times higher than other specialties (Fig. 8 upper). In fact, we are rivaled only by cardiac surgery in clinical output. In addition, despite the relative devaluing of many procedures and the bundling of codes for complex procedures, the growth of RVUs produced per full-time equivalent continues, over the past 7 years (Fig. 8 lower).

What is driving this productivity? The primary driver of resources in the current system is clinical growth. If one reviews the average hospital contribution-to-margin driven by a neurosurgeon, it is over 3 million dollars. In most hospitals, neurosurgeons are the most valuable specialty commodity. The clinical mission of the hospital and the academic mission of the medical school are largely underwritten by the busy surgeons. Thus, revenue generation by neurosurgical clinical activity is valued by the system more than our research and academic output.

Neurosurgical Academic Productivity

Now, let us look at another metric, that being a measure of academic contribution. The h-index bibliometric has become a common tool to measure the academic productivity of an individual, a department, or even a spe-

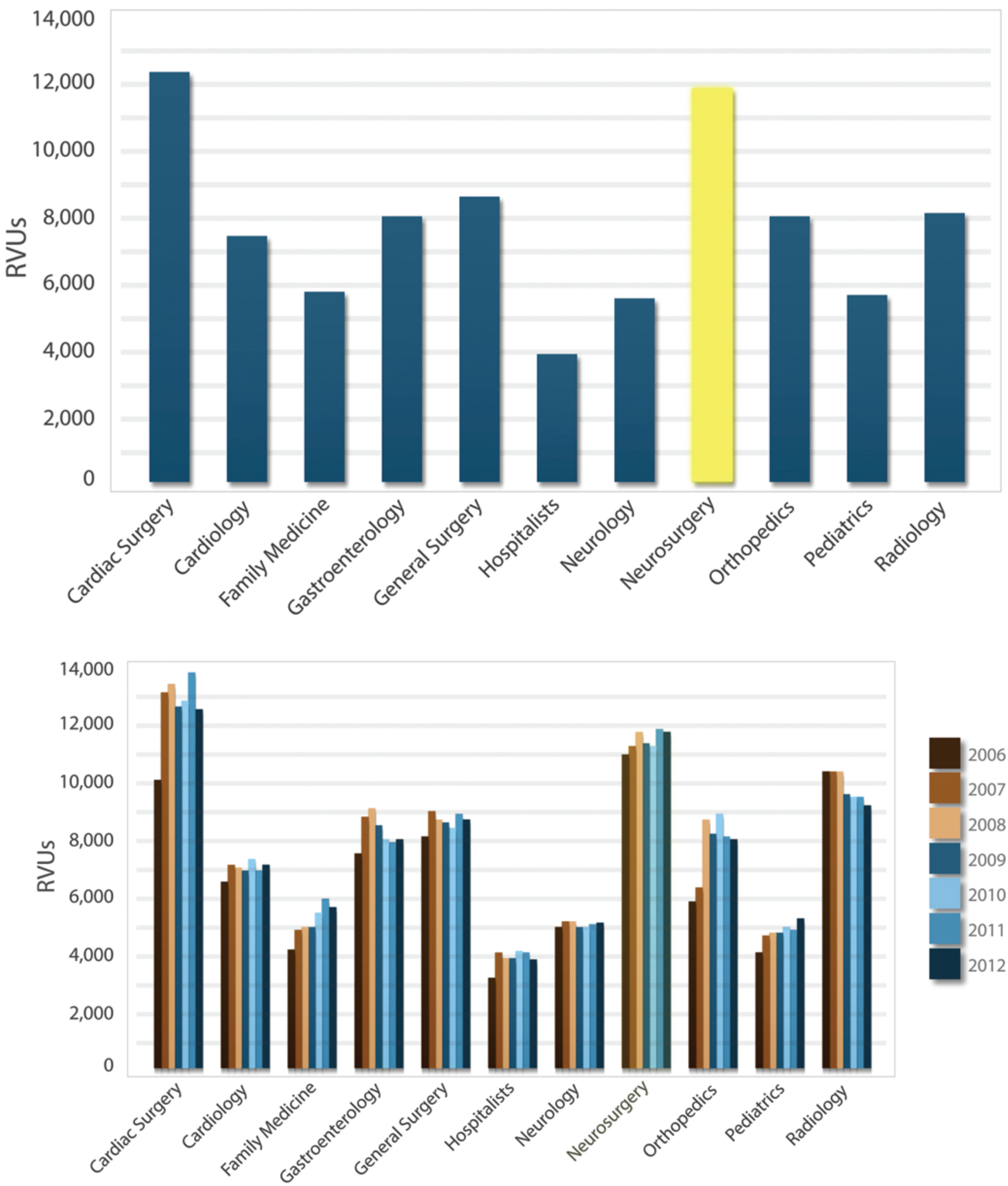


Fig. 8. Graphs illustrating RVUs produced by neurosurgeons relative to other specialties for 1 year **(upper)** and for a 7-year period **(lower)**. (Data from University Healthcare Consortium, 2013.)

cialty. The h-index combines the number of publications and their impact, as judged by number of citations of the work.[29] If we look at academic contributions of neurosurgeons as measured by the h-index (Fig. 9 upper), it is relatively high, as might be expected from the talent and work ethic our members represent.[20,40]

In further analysis, there is an interesting relationship between RVUs and h-index. Figure 9 (lower) demonstrates h-index compared between surgical and medical specialties.[20] Academic prominence increases in both surgical and medical specialties with increasing seniority. However, there is a more subtle trend to be noted. The medical specialists outpace the surgical disciplines during the course of their career, despite starting at similar impact levels during their early attending years. Their greater success with academic career development may indicate that they have more time to focus on their academic contributions rather than on clinical service. To illustrate this in a real way, consider Fig. 10, which demonstrates the publications and grant funding in relation to the number of neurosurgeons available to cover call at our children's hospital. When the number dropped from 4 to 3 surgeons, productivity declined, but it rose again directly after the recruitment of another surgeon.

All of this raises the question of whether we are doing the best for our talented recruits and our specialty as a whole. The alignment of incentives for clinical work is becoming stronger with these recessionary times and tight hospital budgets. In terms of clinical productivity, our recruits are achieving well. But I would challenge that we are not incentivizing them in a way that optimizes the progress of our specialty.

Let me provide a dramatic example of how a society may waste the talent of a generation. In 1958, Chairman Mao Zedong, who was at that time the leader of the People's Republic of China, launched the "Great Leap Forward."[37,56,60] This plan was intended as an alternative to the Soviet economic model focusing on heavy industry. During the period referred to as the "Cultural Revolution," a large segment of the population was forcibly displaced, most notably with the transfer of urban youth to rural regions during the "Down to the Countryside Movement."[52] Many of our Chinese colleague neurosurgeons who grew up in this period know this well, and as intellectuals and urban youths were themselves displaced to rural labor camps. Wei Zhang, a Chinese neurosurgeon and previous fellow of mine now working at the National Institutes of Health (NIH), is one such example. He and his brother were displaced during this time. His older brother spent 8 years, from ages 16 to 24, working in the rice fields (Fig. 11).

The effect of 2 decades of the Cultural Revolution was a paralysis of the Chinese education system. University entrance exams were canceled; intellectuals were sent to labor camps or fled the country; and historical artifacts, books, and paintings were destroyed, leading to huge numbers of poorly educated individuals. Despite its name, the Great Leap Forward was also characterized by a dramatic period of economic regression.

These outcomes are a dramatic example of the waste of talent and the lasting consequences of the missed opportunity of a generation. One can draw direct comparison with our current incentives for clinical work that supersede all others—we are increasingly valued for our technical skills and clinical contributions rather than intellectual contribution. For most neurosurgeons, this is an enjoyable endeavor. I, for one, find technical neurosurgery a most satisfying aspect of my work; however, we are minimizing the contributions that our talented recruits could make to other aspects of our specialty. One such example is the relative lack of current NIH funding generated by neurosurgical investigators relative to other specialties (Fig. 12).

Workforce Planning

Let us take a look at our current neurosurgical workforce and pipeline. The shortage of primary care physicians has been well publicized. What has not been as well publicized is the number of specialists that will also be needed. We can expect a deficit of roughly 65,000 physicians within primary care and the specialists groups by 2025.[4,35]

If we look specifically at surgeons, some interesting trends are apparent. The growth of specialist surgeons has been essentially flat over recent years (Fig. 13)[51] at the same time that our population is aging and the demand for both our primary care and specialty services increases.[57] Furthermore, among the surgical specialties, neurosurgery has experienced tepid growth compared with some other specialties.[51] In addition to slow growth in our numbers, the median age of practicing neurosurgeons is a relatively advanced 54 years.

Next, let's review the trends in the residency slots over time. There has been steady growth in the number of postgraduate positions, with an uptick in the recent years of the match.[46] So what are the rates of growth of the different specialties? For neurosurgery, the number of resident positions in Accreditation Council for Graduate Medical Education (ACGME)–approved residency training programs has grown slowly.[35] If we look at the number of positions offered in last year's 2013 match and then the 5-year trend from the NRMP for neurosurgery and other specialties (Fig. 14),[46] as expected, we see the relatively small numbers of neurosurgical residents matching compared with other specialties. More important, however, is the relative lack of growth within our specialty. The numbers presented above the graphs indicate the extra positions matched in each specialty over the last 5-year period. Although we think we are growing, when we look at our numbers, the growth is being dwarfed by that of other specialties. Table 1 represents the proportional growth of each entering class over the last 5-year period. With the mandate of the federal government and many medical schools to enhance growth in primary care, there have been large increases in family practice and primary medicine. The growth of neurology positions is also impressive, up 19%. In comparison, neurosurgery positions have risen less than 7% over the same interval. If we look at these specialties relative to the growth of all postgraduate slots, we see that the growth of all postgraduate year (PGY)-1 positions has been about 16% and that of neurosurgery almost 7%; however, neurosurgery as a percentage of overall positions has declined from 0.76% 5 years ago to 0.69% in 2013, a 10% relative decline. This is a continued decrement from the

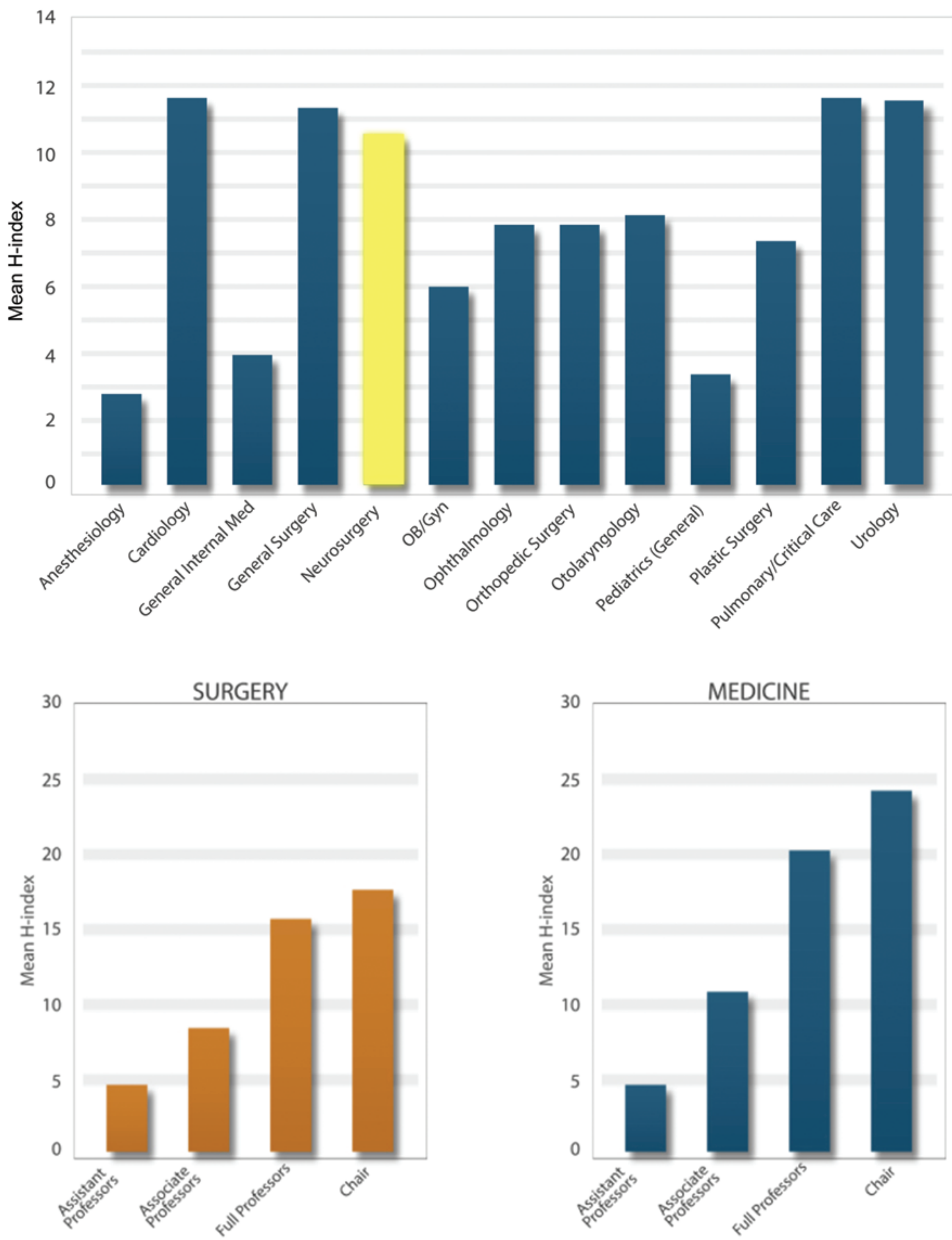


Fig. 9. **Upper:** Graph illustrating mean h-index for neurosurgeons relative to those in other specialties. **Lower:** Graph showing comparison of h-index between medical and surgical specialties by rank of practitioner. (Lower graphs reproduced with permission from Eloy JA, Svider PF, Cherla DV, Diaz L, Kovalerchik O, Mauro KM, et al.: Gender disparities in research productivity among 9952 academic physicians. **Laryngoscope 123:**1865–1875, 2013. © 2013 The American Laryngological, Rhinological and Otological Society, Inc.) Upper graph created by the authors with data from the same study by Eloy et al.

close to 1% of all physicians applying for neurosurgery residency positions when I entered the match in the early 1980s.

This evolving void may also be the motivation for the growth of osteopathic neurosurgical residency programs over the past 2 decades. Match data for these programs indicate that their numbers now constitute approximately 10% of those in our allopathic neurosurgery match.[45]

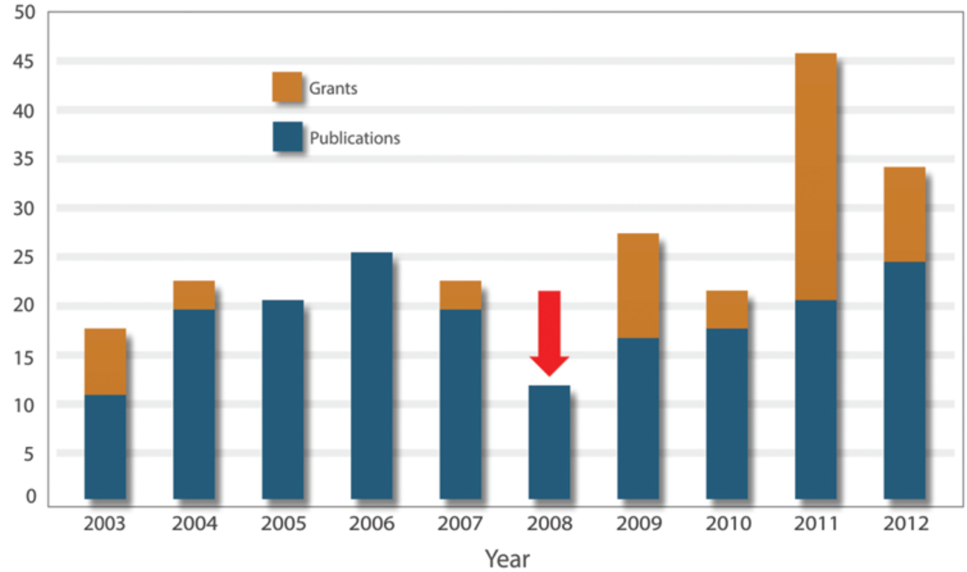


Fig. 10. Graph showing grant applications and publications by pediatric neurosurgeons at Primary Children's Hospital, University of Utah. *Arrow* indicates period when the number of surgeons dropped. (Courtesy of Jay Riva-Cambrin, M.D.)

The challenge of workforce planning is complicated. What we do know is that the population is growing and graying, demanding more services. There is an expected physician shortage, including specialists. Medical advances are increasing utilization over the course of a person's lifespan. As such, our current estimates may be short if life expectancy continues to increase.

Furthermore, there is inhomogeneity in neurosurgical coverage per capita throughout the country and also within counties.[51] Although there is wide variability in neurosurgeons per capita, in the US, the significant amount of spine surgery performed by neurosurgeons increases demand for our services. What is clear from an analysis of market demand, which remains robust, is that we can definitely employ more neurosurgeons.

Fig. 11. Photograph showing NIH researcher Wei Zhang and his brother, while they were living in China. (Courtesy of Wei Zhang, Ph.D.)

The Next Accreditation System

The current reconfiguration of residency training offers us great opportunity. The "Next Accreditation System" is a new paradigm in residency training (https://www.acgme.org/acgmeweb/tabid/435/ProgramandInstitutionalAccreditation/NextAccreditationSystem.aspx). This system will enable well-functioning training programs to innovate. The 7-year program will enable significant time for elective training, including possible enfolded subspecialty training. This may represent an important mechanism to provide subspecialty exposure for our trainees without lengthening training.

The next concern is "fungible" subspecialty areas. I am using the term "fungible" to describe those clinical areas that can be cared for by other specialties. These include endovascular care, which could be managed by neuroradiology, neurology, and now cardiology, as well as critical care, pain, peripheral nerve, and spine. Unless neurosurgery as a specialty focuses its energy on these areas, it will become an expansion target for other specialties.

"Blue Ocean Strategy"

I would like to describe a concept to you that has been coined the "Blue Ocean Strategy." The model refers to a Red Ocean as a business market that exists today, while a Blue Ocean refers to an unknown and untapped market.[38]

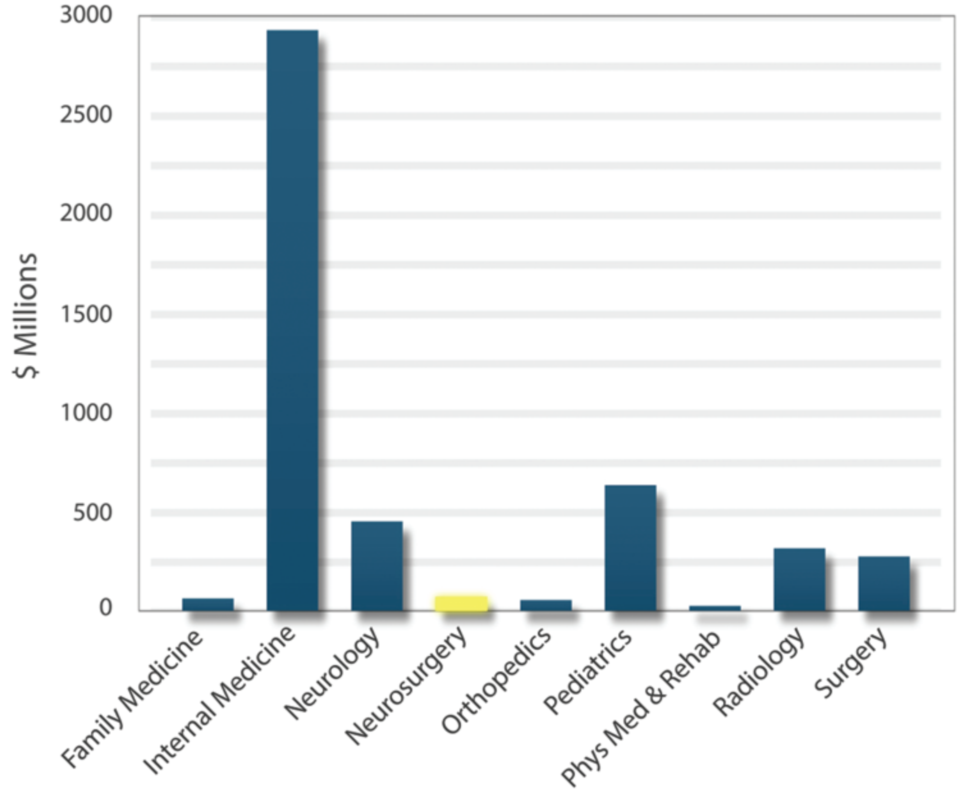


Fig. 12. Graph demonstrating NIH funding by specialty. (Data for 2013 from Blue Ridge Institute for Medical Research.)

Let me provide a personal anecdote to illustrate this principle. While I was a medical student at McGill University in 1983, folk musician Guy Laliberté, who had previously toured Europe and had also learned the technique of fire breathing, and his colleague Gilles Ste-Croix started a small troupe of street performers using talent from a local youth hostel. Originally intended to be a 1-year project, Le Cirque de Soleil experienced such success that it played every summer at the Old Port of Montreal, which was managed by my brother-in-law. The subsequent history is nothing short of fantastic—over the last 30 years they have developed into a worldwide organization, with more than 5000 employees and over a billion dollars in revenue yearly. They did this by creating a new market—defined by a clever fusion of street performance, acrobatics, and illusionists—their Blue Ocean. I would like to apply this principle to our practice of neurosurgery and how we create new markets around us.

In neurosurgery, one of our most pressing Blue Ocean opportunities is neurocritical care. These units are now referred to as "neurocritical care units," but I recall them being referred to as "neurosurgical intensive care units (ICUs)," representing the majority of the patients that occupied the beds. Just over 10 years ago, several associations in neurology established a certification council (United Council for Neurological Subspecialties, or

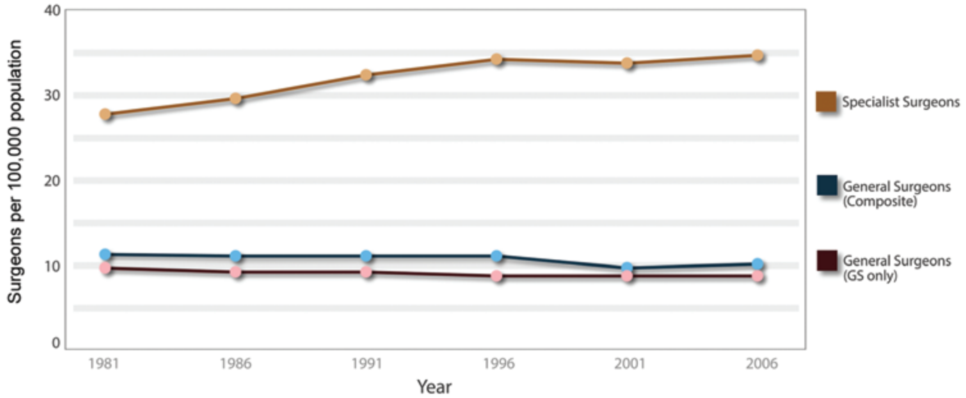


Fig. 13. Graph showing number of general and specialist surgeons. (Modified with permission from Poley S, Belsky D, Gaul K, Ricketts T, Fraher E, Sheldon G: Longitudinal Trends in the U.S. Surgical Workforce 1981–2006: Overall growth has stalled; general surgery supply contracting. Chapel Hill, NC: American College of Surgeons Health Policy Research Institute, 2009.)

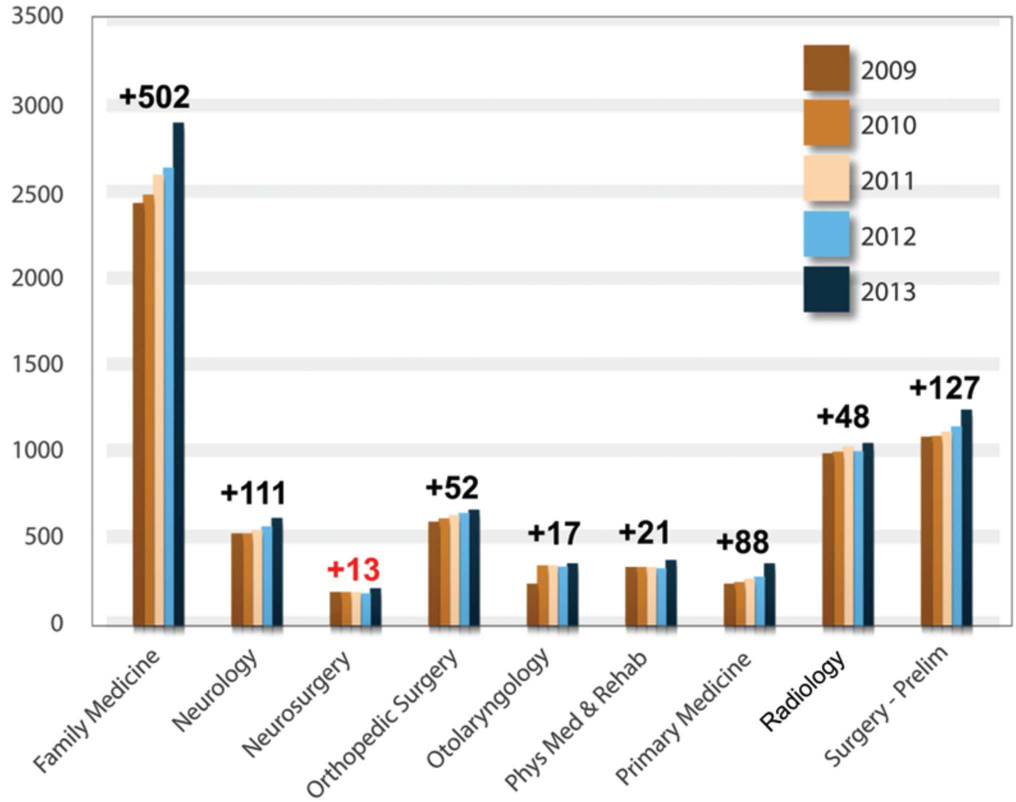


Fig. 14. Graph illustrating number of resident positions offered by ACGME-approved residency training programs. (Data from National Resident Matching Program: Results and Data: 2013. Washington, DC: National Resident Matching Program, 2013.)

UCNS) as a mechanism to codify subspecialties, accredit training programs, and certify physicians—all laudable goals. They defined neurocritical care as a subspecialty with its own formal match. The programs are thriving, with 81 positions offered at last year's match. While this has been an effective mechanism for coordinating care and standardizing training, it has excluded some of our membership from caring for their own patients. Let me also emphasize that with combined competency in critical care and endovascular training, neurology is in a position to usurp neurosurgery in the care of a large segment of vascular disease that we have traditionally thought of as our own—notably subarachnoid hemorrhage and aneurysm treatment.

This career path represents a significant opportunity for our residents. With the accreditation from the Committee on Advanced Subspecialty Training (CAST) of the Society of Neurological Surgeons (SNS), we have a comparable mechanism for accreditation of programs and certification of trainees. The numbers are significant, as attested to by the number of positions in the UCNS match. Within our own department of about 20 neurosurgeons, we can employ 5 critical care specialists to cover our 23-bed ICU. Thus, about 1 critical care position is created by the business generated by 4 neurosurgeons—a considerable opportunity.

Our residency redesign offers similar opportunities to develop skills in other Blue Ocean subspecialty areas, such as endovascular surgery or the expanding indications for functional neurosurgery. One opportunity for our residents to pursue is the AANS residency courses, which have been carefully designed to complement training and offer exposure to various areas of neurosurgery. These courses are fully funded, including travel and accommodation. The faculty are all seasoned educators and recognized subspecialists. Statistically, there is an opportunity for every resident in the country to participate in at least one course. The participants are chosen based on geographical location and the scope of their own training program.

In addition to clinical areas, there is another Blue Ocean opportunity that our talented recruits could pur-

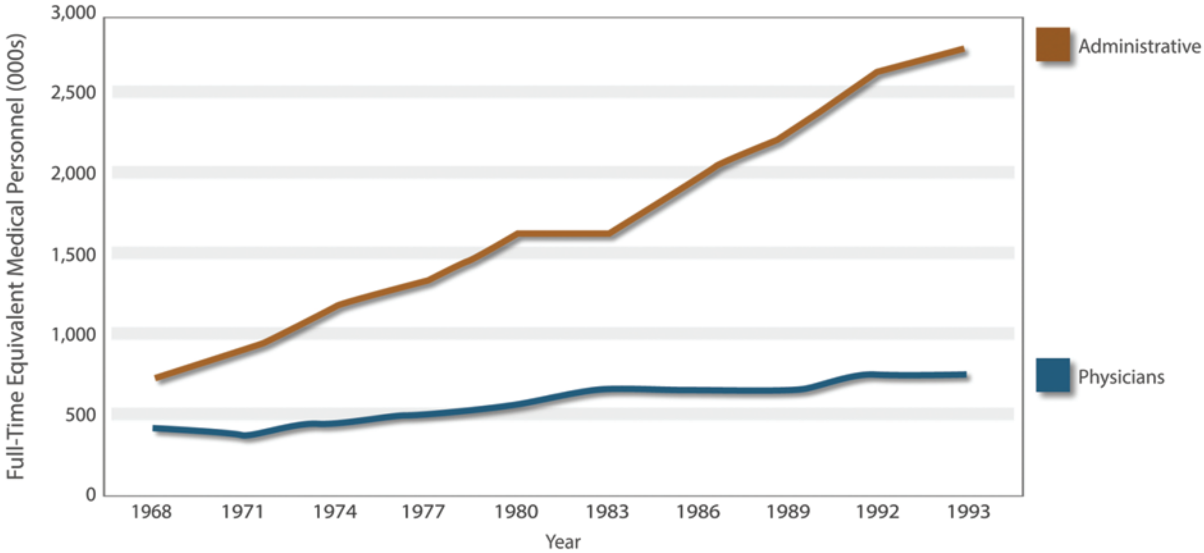
TABLE 1: Proportional growth of each entering class by specialty over the last 5-year period*

Specialty	5-Yr Change	% 5-Yr Change
family medicine	502	19.8
neurology	111	19.1
neurosurgery	13	6.8
orthopedic surgery	52	8.1
otolaryngology	17	6.2
physical medicine & rehabilitation	21	5.6
primary medicine	88	35.6
radiology	48	4.4
surgery–preliminary	127	11.0

* Data from National Resident Matching Program.[46]

sue. Health care in this country is a growth industry. The industry's 23% growth over the past decade dwarfs the 2% growth rate seen in all other industries.[26] While we would like to see all of this growth translate to better patient care, we know that the growth of administration has outstripped the growth in health care providers, as is evidenced by the slope of the curves shown in Fig. 15 (upper). We must reduce the complexity of administration, which is a significant driver of cost in the American system.

Physician input into administration is often lacking. There is evidence that having physician leadership allows a hospital to identify changes that improve care and achieve higher-quality scores in ratings such as that of *U.S. News and World Report* (Fig. 15 lower).[24] Residents and fellows are currently not trained to be successful in this new environment. In response to this Blue Ocean, my partner, Meic Schmidt, and our medical school dean, Vivian Lee, both having obtained additional M.B.A. degrees, have proposed a program for our trainees that could be integrated into a residency curriculum (Table 2). The program curriculum is designed to provide an overview of the foundations and concepts of health care management. It will teach business vocabulary to improve communication between doctors and administrative managers and will develop leadership.



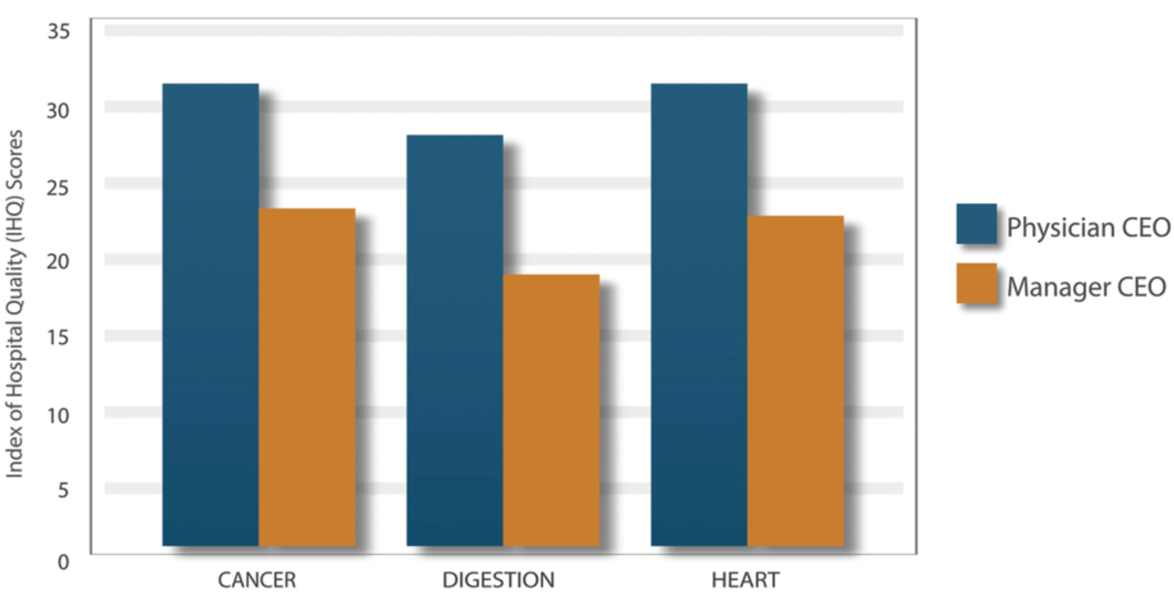


Fig. 15. Upper: Graph showing rate of growth in administrative positions and health care provider positions in US health care. (Data obtained from Himmelstein DU, et al: **American Journal of Public Health. 86:**172–178, 1996).[28] **Lower:** Graph showing *U.S. News and World Report* ratings of hospital quality for hospitals with Chief Operating Officers with medical degrees and for those with business/management training. (Reprinted from Goodall AH: Physician-leaders and hospital performance: is there an association? **Soc Sci Med 73(4):**535–539, Copyright 2011, with permission from Elsevier.)

TABLE 2: "Mini MD-MBA" curriculum topics*

accounting	
	basic financial statements
	cost accounting
finance	
	budgeting
	managing growth
health care systems	
	CMS
	health insurance market
	hospital organization
operations	
	lean principles†
	process analysis
	quality improvement
strategy	
	strategic analysis tools
leadership & negotiation	
	new leadership models
	effective teamwork
	collaborative negotiation skills
marketing strategies	
	communication
patient communication	
	electronic communication
	electronic health record

* CMS = Centers for Medicare and Medicaid Services.
† Principles developed by Japanese manufacturers to combat waste.

The Future

So, here is our challenge: The population is increasing, and developed nations are graying. The specialist shortage is worsening, and we have a demand for more neurosurgeons. There has never been a time when the need for our services has so expanded.

We are at a crossroads. We can continue to do what we have done very well, consider ourselves elite specialists, and demand resources based on our limited supply. However, I propose to you that this tactic will work only as long as there are not other physicians or technologies to provide these services to our patients. Let me provide some perspective on this. The bars on this graph demonstrate some of the most important developments in human history (Fig. 16). The y-axes denote the world population on the left and the social development index on the right. Andrew McAfee, of the Massachusetts Institute of Technology, argues that the most critical element that led to the bending of these curves was the advent of technology. Not religion, nor exploration, nor empires that have come and gone.[44]

I provide two recent anecdotes to emphasize this point. The Google car is one of several driverless cars in development. In 2012, the team announced that they had completed over 300,000 driving miles accident free, by using a range finder mounted on the top of the car that generates a detailed 3D map of its environment (http://googleblog.blogspot.com/2012/08/the-self-driving-car-logs-more-miles-on.html). The car then takes these generated maps and combines them with high-resolution maps, producing data models that allow it to drive itself. Mercedes, just in the past 6 months, has propelled a driverless sedan across Germany. As of December 2013, 4 US states have passed laws permitting autonomous vehicles. Just imagine how this may impact the millions of professional

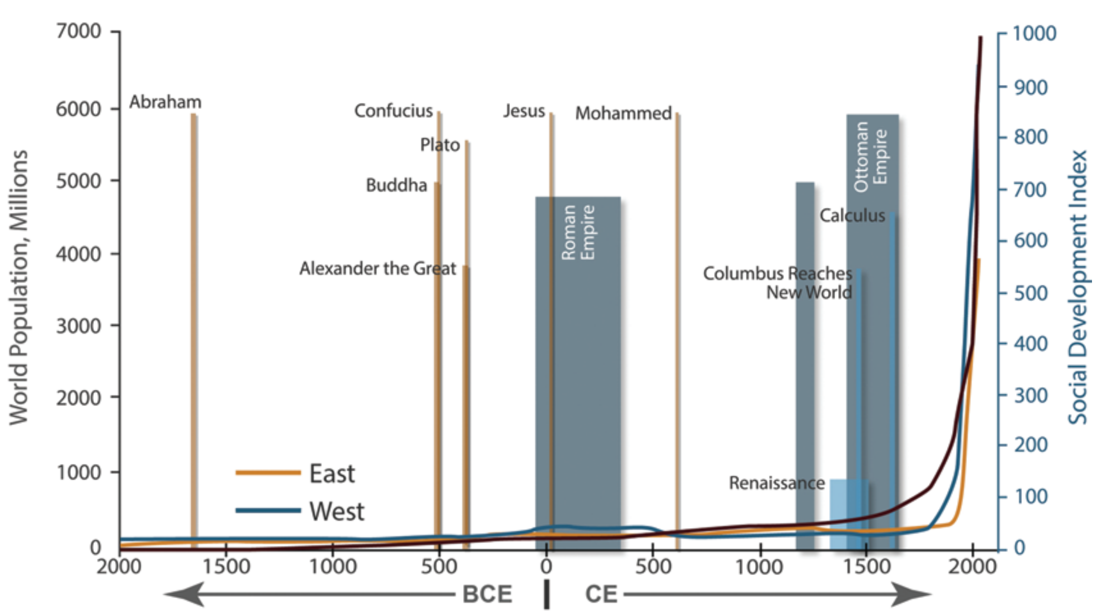


Fig. 16. Graph showing social development index (right y axis: *brown line* = East; *blue line* = West) and world population (left y-axis: *black line*) relative to the occurrence of important developments in human history. (Reproduced with permission from McAfee A: Are droids taking our jobs? TEDxBoston 2012: TED; 2013.)

drivers in the trucking and taxi industries. The next anecdote I describe began closer to my home in Utah. Ken Jennings, a Brigham Young University graduate, is known for winning 74 games in a row on the game show *Jeopardy!* in 2004. In February 2011, *Jeopardy*'s "IBM Challenge" featured the company's Watson computer against Jennings and another competitor. Watson won the competition. Human performance was quickly matched and surpassed by Watson during its development. Emphasizing the potential of others—in this case, computers—to supersede us, underneath his response during the final *Jeopardy!* round, Jennings wrote on his screen "I for one welcome our new computer overlords."

Let us also be reminded by the story of cardiothoracic surgery over the past generation. When I was a medical student, the luminary cardiac surgeons were at the top of the medical food chain. Michael DeBakey was one of the most courageous and innovative physicians in history. During his pioneering career, he saw the routine deployment of aortic grafts, cardiac arterial bypass, and carotid endarterectomy.[15–17] However, cardiac surgery did not embrace the radical new technology of endovascular surgery, nor did they view themselves as the primary caregivers of their patients. As a result, the now-denoted "cardiovascular disease" specialty is much larger and more competitive, as measured by the NRMP results, than thoracic surgery, which, in contrast, is dwindling and not filling their positions. Cardiac surgery clearly did not evolve as a specialty with the advent of innovative technology.

I would argue that the rapid technical advances that impact much of our core neurosurgery will enable those with less experience and training in their own residencies to master what we have, in less time. These advances will make the precise work on which we pride ourselves more accessible to other specialties; they have also produced a phenomenon that I have witnessed, which is that 10 or 20 years of microsurgical subspecialty experience such as with open aneurysm or skull base surgery may not be necessary to reach the top of your game. Technology has enabled the treatment of some intracranial aneurysms with less morbidity to the patient and with improved functional outcomes. The training to become proficient in these techniques may be facilitated by simulation. For example, patient-specific models for endovascular treatment of an aneurysm are now readily available for rehearsal prior to endovascular treatment (Fig. 17). Modeling of patient-specific surgical anatomy with present-day 3D printers will facilitate procedural rehearsal and will become routine. Placement of specific spinal implants or pedicle screws may also be rehearsed. All of these technical advances will make training more relevant and efficient. With evolving technology, the treatment of some of our most complex surgical problems will be simplified, using minimally invasive techniques and rehearsal.

In the final analysis, I think that the key to remaining relevant with the incorporation of new technologies to the treatment of our patients will be to retain control of the care of our patients, and to be flexible, open-minded, and nimble with the adaptation of these new procedures. I am in awe of my colleagues and of the young people that are attracted to neurosurgery. We can train and encourage them to pursue areas of our specialty that we create or have neglected. To achieve this, we need to expand our residency slots and provide appropriate mentorship in each of these areas.

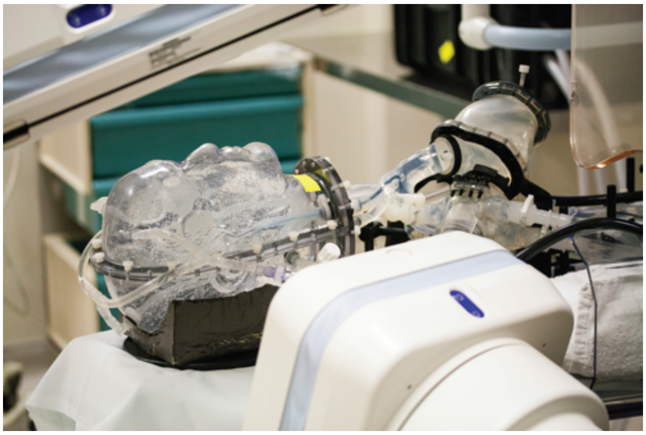


Fig. 17. Photograph showing a patient-specific model for endovascular aneurysm treatment. (Reproduced with permission from the Department of Neurosurgery, University of Utah.)

It is certainly not hard for neurosurgeons to compete if the playing field is level. We can achieve this if we take the leap and put all of our energy toward it. It is a remarkable time in our specialty and we should embrace it with all of our spirit. Our future is bright; let us define it.

Acknowledgments

We thank Jennie Williams, M.A., for fantastic help in putting this presentation together. Dr. Couldwell also wishes to thank all of the membership for the distinct privilege of representing the AANS this year.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

References

1. Adson AW, Ott WO: Preservation of the facial nerve in the radical treatment of parotid tumors. **Arch Surg 6:**739–746, 1923
2. Beecher HK: The first anesthesia records (Codman and Cushing). **Surg Gynecol Obstet 71:**689–693, 1940
3. Brothwell DR: Notable examples of early trephining, in Oakley KP, Brooke WMA, Akester AR, et al (eds): **Contributions on Trepanning Or Trephination in Ancient and Modern Times.** London: Royal Anthropological Institute of Great Britain and Ireland, 1959, pp 95–96
4. Center for Workforce Studies: 2013 State Physician Workforce Data Book. **Association of American Medical Colleges.** (https://www.aamc.org/download/362168/data/2013statephysicianworkforcedatabook.pdf) [Accessed September 1, 2014]
5. Copper IS: Cryogenic surgery: a new method of destruction or extirpation of benign or malignant tissues. **N Engl J Med 268:** 743–749, 1963
6. Cushing H: Haematomyelia from gunshot wounds of the spine. A report of two cases, with recovery following symptoms of hemilesion of the cord. **Am J Med Sci 115:**654–683, 1898
7. Cushing H: **The Pituitary Body and Its Disorders: Clinical States Produced by Disorders of the Hypophysis Cerebri.** Philadelphia: JB Lippincott Co., 1912

8. Cushing H: Some principles of cerebral surgery. **JAMA 52:** 184–195, 1909
9. Dandy WE: A method of restoring nerves requiring resection. **JAMA 122:**35–36, 1943
10. Dandy WE: An operation for the treatment of spasmodic torticollis. **Arch Surg 20:**1021–1032, 1930
11. Dandy WE: Pneumoperitoneum: a method of detecting intestinal perforation—an aid in abdominal diagnosis. **Ann Surg 70:**378–383, 1919
12. Dandy WE: Ventriculography following the injection of air into the cerebral ventricles. **Ann Surg 68:**5–11, 1918
13. Das K, Benzil DL, Rovit RL, Murali R, Couldwell WT: Irving S. Cooper (1922–1985): a pioneer in functional neurosurgery. **J Neurosurg 89:**865–873, 1998
14. Dealy JB Jr: Merrill Clary Sosman, 1890–1959. **J Neurosurg 17:**555–557, 1960
15. DeBakey ME: Successful carotid endarterectomy for cerebrovascular insufficiency. Nineteen-year follow-up. **JAMA 233:** 1083–1085, 1975
16. DeBakey ME: Surgical treatment of atherosclerotic heart disease. **Am J Cardiol 63:**9H–11H, 1989
17. Debakey ME, Crawford ES, Cooley DA, Morris GC Jr, Royster TS, Abbott WP: Aneurysm of abdominal aorta analysis of results of graft replacement therapy one to eleven years after operation. **Ann Surg 160:**622–639, 1964
18. Donaghy RMP, Yaşargil MG: **Microvascular Surgery.** St. Louis: Mosby, 1967
19. El Gindi S: Neurosurgery in Egypt: past, present, and future—from pyramids to radiosurgery. **Neurosurgery 51:**789–796, 2002
20. Eloy JA, Svider PF, Cherla DV, Diaz L, Kovalerchik O, Mauro KM, et al: Gender disparities in research productivity among 9952 academic physicians. **Laryngoscope 123:**1865–1875, 2013
21. Ferembach D, Dastugue J, Poitrat-Targowla MJ: **La Nécropole Épipaléolithique de Taforalt (Maroc Oriental): Étude des Squelettes Humains.** Rabat: Edita-Casablanca, 1962
22. Field AJ: The most technologically progressive decade of the century. **Am Econ Rev 93:**1399–1413, 2003
23. Fulton JF: **Harvey Cushing: A Biography.** Springfield, IL: Charles C Thomas, 1946
24. Goodall AH: Physician-leaders and hospital performance: is there an association? **Soc Sci Med 73:**535–539, 2011
25. Grosvenor AE, Laws ER: The evolution of extracranial approaches to the pituitary and anterior skull base. **Pituitary 11:** 337–345, 2008
26. Healthcare Metro Monitor Supplement: Tracking the role of healthcare in economic recession and recovery in the nation's 100 largest metropolitan areas. **Brookings Institute.** (http://www.brookings.edu/~/media/research/files/reports/2013/06/28%20metromonitor%20health/healthcare%20monitor%20final) [Accessed September 1, 2014]
27. Heuer GJ, Dandy WE:A report of seventy cases of brain tumor. **Bull Johns Hopkins Hosp 27:**224–237, 1916
28. Himmelstein DU, Lewontin JP, Woolhandler S: Who administers? Who cares? Medical administrative and clinical employment in the United States and Canada. **Am J Public Health 86:**172–178, 1996
29. Hirsch JE: An index to quantify an individual's scientific research output. **Proc Natl Acad Sci U S A 102:**16569–16572, 2005
30. Hirsch NP, Smith GB: Harvey Cushing: his contribution to anesthesia. **Anesth Analg 65:**288–293, 1986
31. Hoffman H, Hudgins PA: Head and skull base features of nine Egyptian mummies: evaluation with high-resolution CT and reformation techniques. **AJR Am J Roentgenol 178:**1367–1376, 2002
32. Hole-in-the-head operations. **The New Scientist.** September 3, 1959; Vol 6, No. 146; p 326, 1959
33. Hornyak M, Rovit RL, Simon AS, Couldwell WT: Irving S. Cooper and the early surgical management of movement disorders. Video history. **Neurosurg Focus 11(2):**E6, 2001
34. Huber P, Krayenbuhl H, Yaşargil MG: **Cerebral Angiography.** Stuttgart: Thieme, 1982
35. The Impact of Health Care Reform on the Future Supply and Demand for Physicians Updated. Projections Through 2025. **Association of American Medical Colleges.** (https://www.aamc.org/download/158076/data/updated_projections_through_2025.pdf) [Accessed September 2, 2014]
36. International Department Central Committee of CCP: **Comrade Mao Zedong's Historical Role and Mao Zedong Thought—Resolution on Certain Questions in the History of Our Party Since the Founding of the People's Republic of China (abridged). Adopted by the Sixth Plenary Session of the Eleventh Central Committee of the Communist Party of China on June 27, 1981).** (http://www.idcpc.org.cn/english/maozedong/comments.htm) [Accessed September 3, 2014]
37. Jin Q: **The Culture of Power: Lin Biao and the Cultural Revolution.** Stanford, CA: Stanford University Press, 1999
38. Kim WC, Mauborgne R: **Blue Ocean Strategy: How to Create Uncontested Market Space and Make Competition Irrelevant.** Cambridge, MA: Harvard Business Review Press, 2005
39. Krisht K, Sorour M, Cote M, Hardy J, Couldwell WT: Marching beyond the sella: Gerard Guiot and his contributions to neurosurgery. Historical vignette. **J Neurosurg** [in press],
40. Lee J, Kraus KL, Couldwell WT: Use of the h index in neurosurgery. Clinical article. **J Neurosurg 111:**387–392, 2009
41. Macewen W: An address on the surgery of the brain and spinal cord. **Br Med J 2:**302–309, 1888
42. Margetts EL: Trepanation of the skull by the medicine-men of primitive cultures, with particular reference to present-day native East African practice, in Brothwell D, Sandison AT (eds): **Diseases in Antiquity: A Survey of Diseases, Injuries and Surgery of Early Populations.** Springfield, IL: Charles C Thomas, 1967, pp 637–701
43. Marx M, D'Auria SH: CT examination of eleven Egyptian mummies. **Radiographics 6:**321–330, 1986
44. McAfee A: Are droids taking our jobs? **TED.** (https://www.ted.com/talks/andrew_mcafee_are_droids_taking_our_jobs) [Accessed September 1, 2014]
45. National Matching Services: Outcomes and trends in the AOA match. Presentation to AACOM, April 4, 2014. **National Matching Services.** (https://www.natmatch.com/aoairp/stats/AACOM-NMS-Apr4-14.pdf) [Accessed September 1, 2014]
46. National Resident Matching Program: Results and data: 2013 Main Residency Match®. **National Resident Matching Program.** (http://www.nrmp.org/wp-content/uploads/2013/08/resultsanddata20131.pdf) [Accessed September 1, 2014]
47. National Resident Matching Program, Association of American Medical Colleges: Charting outcomes in the match. Characteristics of applicants who matched to their preferred specialty in the 2011 main residency match, 4th edition. **National Resident Matching Program.** (http://www.nrmp.org/wp-content/uploads/2013/08/chartingoutcomes2011.pdf) [Accessed September 1, 2014]
48. Nunn JF: **Ancient Egyptian Medicine.** London: British Museum Press, 1997
49. Oakley K, Brooke W, Akester A, Brothwell D: Contributions on trepanning or trephination in ancient and modern times. **Man (Lond) 59:**92–96, 1959
50. Panourias IG, Skiadas PK, Sakas DE, Marketos SG: Hippocrates: a pioneer in the treatment of head injuries. **Neurosurgery 57:**181–189, 2005
51. Poley S, Belsky D, Gaul K, Ricketts T, Fraher E, Sheldon G: Longitudinal trends in the U.S. surgical workforce 1981-2006: Overall growth has stalled; general surgery supply contracting. **American College of Surgeons Health Policy Research In-**

stitute. (http://www.acshpri.org/documents/ACSHPRI_FS1.pdf) [Accessed September 1, 2014]

52. Schoppa RJ: **Revolution and Its Past: Identities and Change in Modern Chinese History.** Upper Saddle River, NJ: Pearson Education, 2006
53. Selin H, Shapiro H: **Medicine Across Cultures: History and Practice of Medicine in Non-Western Cultures.** Dordrecht: Kluwer Academic Publishers, 2003
54. Stewart TD: **Stone Age Skull Surgery: a General Review, With Emphasis on the New World.** Washington, DC: Smithsonian Institution, 1958
55. Tew JM Jr: M. Gazi Yaşargil: Neurosurgery's man of the century. **Neurosurgery 45:**1010–1014, 1999
56. Tsou T: **The Cultural Revolution and Post-Mao Reforms: A Historical Perspective.** Chicago: University of Chicago Press, 1986
57. US Department of Health and Human Services, Health Resources and Services Administration, Bureau of Health Professions: **The Physician Workforce: Projections and Research into Current Issues Affecting Supply and Demand.** Washington, DC: Department of Health and Human Services, 2008 (http://bhpr.hrsa.gov/healthworkforce/reports/physwfissues.pdf) [Accessed September 2, 2014]
58. Verano JW, Williams JM: Head injury and surgical intervention in pre-Columbian Peru. **Am J Phys Anthropol Suppl 14:** 167–168, 1992 (Abstract)
59. Voorhees JR, Cohen-Gadol AA, Laws ER, Spencer DD: Battling blood loss in neurosurgery: Harvey Cushing's embrace of electrosurgery. **J Neurosurg 102:**745–752, 2005
60. Worden RL, Savada AM, Dolan RE (eds): **China: A Country Study, ed 4.** Washington, DC: Federal Research Division, Library of Congress, 1988

Manuscript submitted August 4, 2014.

Accepted August 28, 2014.

Please include this information when citing this paper: DOI: 10.3171/2014.8.JNS141791.

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